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Post-early Messinian counterclockwise rotations on Crete: implications for Late Miocene to Recent kinematics of the southern Hellenic arc

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Abstract

Most geodynamical models for the kinematics of the central Mediterranean recognise that major tectonic rotations must have played an important role during the Neogene. The Hellenic arc is believed to have been subjected to clockwise rotations in the west and counterclockwise rotations in the east, while the southern part (Crete) shows no rotations (Kissel and Laj, 1988). Many qualitative and quantitative models are based on the idea that Crete did not rotate. We present new palaeomagnetic data which show that post-early Messinian counterclockwise rotations have occurred on Crete. The amount of counterclockwise rotation generally varies between 10º and 20º, but in central Crete much larger rotations (up to ~40º counterclockwise) were found. Only a few sections did not show any rotation. The anisotropy of magnetic susceptibility (AMS) shows lineations, which are consistently WNW–ESE throughout Crete, indicating post-rotational WNW–ESE extension, or NNE–SSE compression. The observed counterclockwise rotations are consistent with the results of tectonic modelling by Ten Veen and Meijer (1998). The latter study compares the late-Middle Miocene to Recent kinematics with modelled intra-plate stresses for various possible distributions of plate boundary forces. Observations reveal that motion along left-lateral and right-lateral faults occurred during the Pliocene. The model analysis shows these motions to be consistent with transform resistance along the eastern segment of the overriding margin. The counterclockwise block rotations observed by us are probably a consequence of displacements along the left-lateral and right-lateral faults and could reflect a similar tectonic regime that involved transform resistance.

Keywords: Messinian; counterclockwise rotation; Crete; Hellenic arc; palaeomagnetic rotations

1. Introduction

The origin and evolution of the Hellenic arc (Fig. 1) system is primarily controlled by the effects of continent–continent collision due to relative motion of the African and European plates. In the subsequently developing land-locked configuration of the Mediterranean basin, southward roll-back of the trench system induced arc migration which ultimately shaped the present-day geometry of the arc system (Wortel and Spakman, 1992). Seismic tomography has shown that the African plate subducts to a depth of 200 km at the longitude of Crete (Spakman et al., 1988). Slab pull on the subducted plate caused a southward retreat (roll-back) of the subduction zone, generating extension in the Aegean Sea and the movement of Crete to the south (Le Pichon,

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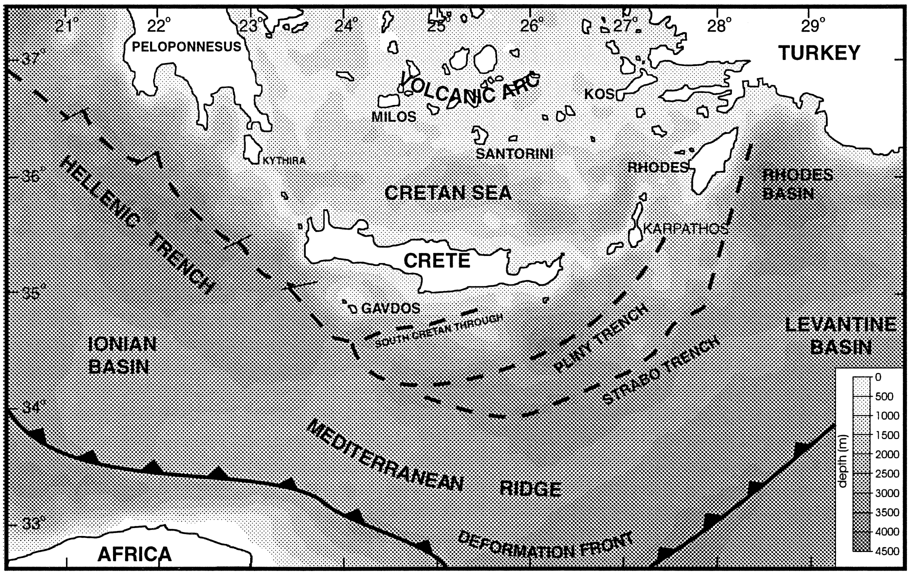


Fig. 1. Major structural features and bathymetry of the Aegean region.

1982; Meulenkamp et al., 1988). Important changes in the palaeogeography during late Serravallian and early Tortonian times (Miocene) can be attributed to the initiation of the slab roll-back process. Migration of the trench system to the southwest, estimated at 12–11 Ma, gave rise to an extensional regime within the back-arc domain, which led to general subsidence (Angelier et al., 1982).

The extension in the Aegean region occurred shortly after a crustal thickening episode, which culminated in the Late Eocene (Blake et al., 1981; Bonneau and Kienast, 1982). Crustal thickening, by imbrication of thrust slices, was active in the Eocene in the central Aegean Cycladic region (Bonneau, 1982), after which extension was active in the Early Miocene. At that time crustal thickening was probably still active in the most external zones (Crete) until some time during the (late) Middle Miocene. The present-day morphology results from large-scale normal faulting cross-cutting the Hellenide nappe pile during the late Neogene and Quaternary (Angelier et al., 1982). Crete appears, following intensive post-orogenic block-faulting as a mosaic of horsts and grabens. The Late Miocene to Recent evolution of the Aegean region is thus dominated by extensional tectonics, although compressional events are also thought to have occurred (Meulenkamp et al., 1988). Existing kinematic models (Le Pichon and Angelier, 1981; Angelier et al., 1982; Taymaz et al., 1991; Westaway, 1991) which attempt to account for the geodynamic development of the Aegean imply that major tectonic rotations must have played an important role during the late Cenozoic evolution of the Hellenic arc.

On the basis of numerous palaeomagnetic studies, Kissel and Laj (1988) concluded that the Aegean arc had an almost rectilinear E–W-trending geometry during the Early Miocene. They further suggested that the current curvature of this region was acquired in two major phases. The first phase, during the Middle Miocene, resulted in clockwise rotations in the west (Epirus) and counterclockwise rotations in western Anatolia (Turkey). The second phase, during the last 5 million years, produced only clockwise rotations for the northwestern part of Greece. According to this reconstruction, Crete did not undergo any rotation since ~7 Ma (Laj et al., 1982), because palaeomagnetic directions from Tortonian sediments on Crete were found to be closely aligned along a N–S direction (Valente et al., 1982).

Recently, Meijer and Wortel (1996, 1997) used a numerical model to analyse quantitatively the horizontal patterns of stress and deformation of the Aegean region during the Pliocene to Recent. Subsequently, Ten Veen and Meijer (1998) applied a similar analysis to the Late Miocene to Recent deformation of Crete. Fault kinematics are based on geological observations, such as lineaments, observed kinematic indicators and relative burial histories and are compared with modelled horizontal stress patterns. These techniques contribute to the understanding of forces that control the state of stress and associated deformation of the overriding continental margin. The Pliocene stress field on Crete, as inferred from kinematic indicators, is consistent with counterclockwise rotation of fault blocks (Ten Veen and Meijer, 1998).

Several cyclo-, bio- and magnetostratigraphic studies on Crete, in addition to earlier studies (Langereis, 1984), establish an integrated stratigraphic time-frame for the late-Middle to Late Miocene time-interval in the Mediterranean. The resulting high-resolution stratigraphic framework (Krijgsman et al., 1994, 1995) has enabled the extension of the astronomical polarity time-scale into the Late Miocene (Hilgen et al., 1995). Here, we use these palaeomagnetic results and apply them to rotational studies, with the added benefit of an accurate timing of possible tectonic rotations. In addition, we have measured the anisotropy of the magnetic susceptibility (AMS) of all the new sections, and we have used the data of Langereis (1984) for the older sections.

The marine sections studied are located throughout Crete (Figs. 4 and 5) and cover part of the Tortonian and Messinian time-span (between 9.7 and 6.7 Ma). For detailed information on the location of the sections, the lithology and accurate age determination of the sediments, we refer to earlier studies (Langereis, 1984; Krijgsman et al., 1994, 1995). The sections are divided into three groups: (1) the Potamida, Skouloudiana, Vasilopoulo, Kotsiana and Apostoli sections on western Crete and the Metochia section on the Island of Gavdos (south of Crete); (2) the sections of Kastelli, Kastellios Hill and Skinias on central Crete; and (3) the Makrilia and Faneromeni sections on eastern Crete. The Koufonisi section is located on the Island of Koufonisi (Figs. 4 and 5). In central Crete, the sections cover the largest time-interval; Skinias contains the oldest sediments of 9.7 Ma and Kastelli the youngest with an age of 6.7 Ma. In western and eastern Crete, the sections cover an interval from approximately 7.9 to 6.7 Ma.

2. Palaeomagnetic results

2.1. Characteristic remanent magnetisation (ChRM) directions

Details of the natural remanent magnetisation (NRM) characteristics can be found in previous studies of Langereis (1984) and Krijgsman et al. (1994, 1995). For this study, we only used the thermal demagnetisation results from samples with relatively high NRM intensities (1–20 mA/m) and showing a linear decay towards the origin, providing the most reliable characteristic remanent magnetisation (ChRM) components. In total, 688 specimens from 12 continuously sampled sections were used (Table 1). In several sections, the results did not meet our reliability criteria. These data are omitted from Table 1 and were not used in this study. Specimens with relatively low intensities, with alterations at high temperatures ($>400°C$), with a large present-day overprint, and which are close to a polarity reversal, were also excluded. Generally, a reasonable to very good precision parameter (k) was found and the mean direction per section shows a small cone of confidence at the 95% level (α_{95}), with the exception of the Kastellios Hill section (Table 1).

The ChRM results reveal counterclockwise rotations for most of the sections studied (Figs. 2 and 4), revealing a pattern of counterclockwise rotations on Crete. The amount of rotation, however, differs from 27–42º counterclockwise on central Crete, to $\sim$12º on eastern Crete (Table 1). The sections on western Crete also show small counterclockwise rotations between 14º and 19º, although two sections (Vasilopoulo, Potamida 1/3) did not reveal any significant rotations. A comparison of the palaeomagnetic directions with those expected from the pole for Eurasia (Besse and Courtillot, 1991) during the Late Miocene (the African pole of the same epoch is not significantly different), indicates that declination rotations (R in Table 1; Butler, 1992) are counterclockwise and vary between 8º and 25º in western and eastern Crete (except for Potamida 1 and 3), whereas in central Crete rotations amount to 33–48º (Table 1). The inclination data of the sections studied generally have values between 40º and 50º, compared to a geocentric axial dipole field value of $\sim$55º, representing an inclination error of 10–15º,

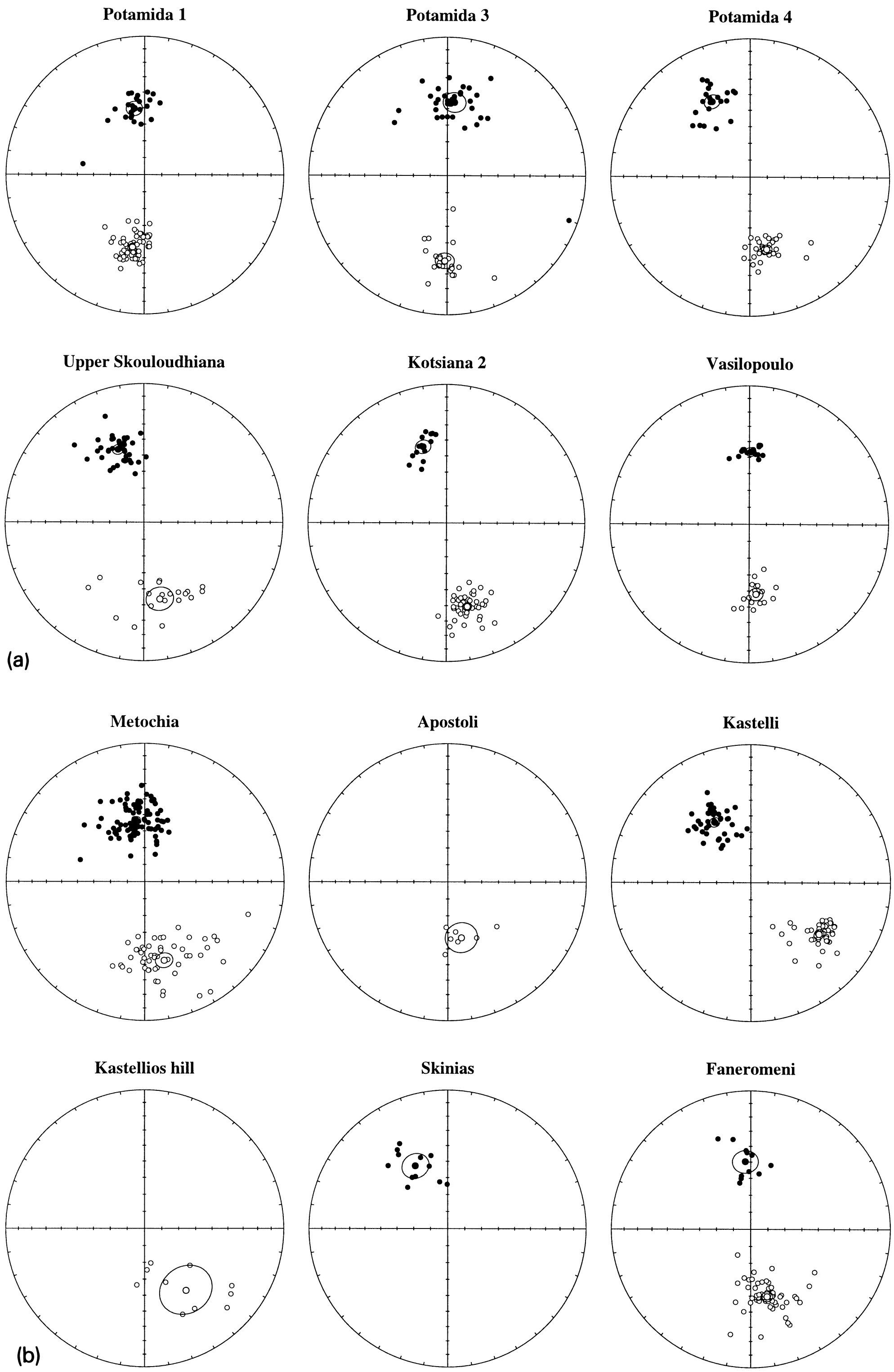

Potamida 1
Potamida 3
Potamida 4
Upper Skouloudhiana
Kotsiana 2
Vasilopoulo
(a)
Metochia
Apostoli
Kastelli
Kastellios hill
Skinias
Faneromeni
(b)

Table 1
Results from NRM and AMS analysis from the different sections on Crete, corrected for bedding tilt

Section	NRM analysis										AMS analysis (k_{max} directions)					
	n	Decl.	Incl.	k	α_{95}	Rot.	R	DR	F	DF	n	Az	Dip	dAz	dDip	L
West Crete [a]																
Potamida 1	97	4.8	47.4	54.6	2.0	4.8 c	0.9	3.1	3.4	2.5	50	97.6	11.1	5.6	1.8	1.0074
Potamida 2											25	29.2	9.4	8.4	3.6	1.0084
Potamida 3	57	3.9	42.9	20.1	4.3	3.9 c	1.8	5.1	7.9	3.9	19	109.9	3.3	10.1	4.0	1.0196
Potamida 4	55	341.2	43.2	48.4	2.8	18.8 cc	−24.5	3.7	7.6	3	14	277.0	15.8	10.3	4.2	1.0108
Skouloudiana	60	343.3	43.5	33	3.2	16.7 cc	−22.4	4.1	7.3	3.2	28	277.6	1.8	23.6	3.0	1.0085
Kotsiana 1											31	286.3	12.7	16.8	3.0	1.0031
Kotsiana 2	62	345.2	38.8	73.1	2.1	14.8 cc	−20.5	3	12	2.6	32	282.3	13.1	6.5	1.5	1.0065
Vasilopoulo	33	357.5	47.2	102.3	2.5	2.5 cc	−8.2	3.6	3.6	2.8	8	287.0	13.4	49.1	7.3	1.0029
Apostoli	7	346.3	55.9	44.9	9.1	13.7 cc	−19.4	13.3	−5.1	7.6	8	44.7	11.4	73.7	5.4	1.0013
Gavdos																
Metochia	144	349.6	48.9	23.7	2.5	10.4 cc	−16.1	3.7	1.9	2.8	22	271.9	0.4	23.1	1.7	1.0090
Central Crete																
Kastelli	83	317.6	43.9	33.7	2.7	42.4 cc	−48.1	3.6	6.9	2.9	36	280.5	5.9	8.4	3.0	1.0045
Kastellios Hill	10	326.3	45.3	11.6	14.8	33.7 cc	−39.4	17.1	5.5	12	11	317.4	18.9	17.2	8.0	1.0108
Skinias	12	332.6	47.9	33.5	7.6	27.4 cc	−33.1	9.3	2.9	6.4	10	278.3	1	20.9	4.7	1.0037
East Crete																
Makrilia											52	33.2	3.2	72.3	9.0	1.0006
Faneromeni	68	347.9	48.7	37.4	2.9	12.1 cc	−17.8	4.1	2.1	3	34	284.1	2.7	3.5	1.8	1.0073
Koufonisi											33	152.2	0.9	13.1	2.3	1.0025

All sections are of the same age (late Tortonian/early Messinian). n = number of specimens; Decl., Incl. = site mean ChRM declination and inclination; k = Fisher's precision parameter; α_{95} = 95% cone of confidence; Rot. = sense of rotation, (c) c = (counter)clockwise with a 0° reference direction; R/F = vertical axis rotation/flattening of inclination (R = positive when clockwise rotation, and F = positive when 'flatter' than expected inclination) and DR/DF as confidence limits (Butler, 1992) with Eurasian Miocene reference pole (Besse and Courtillot, 1991); Az, Dip = mean azimuth and dip of k_{max} axes; dAz, dDip = errors on mean k_{max} axes; L = magnetic lineation (k_{max}/k_{int}).
[a] Marks data previously published by Langereis (1984).

which is characteristic for such sediments (marine marls, clays). The inclination flattening (F in Table 1; Butler, 1992), compared to a Eurasian pole, is typically less than the inclination error.

2.2. Anisotropy of the magnetic susceptibility

The anisotropy of the magnetic susceptibility (AMS) in (weakly) deformed and unmetamorphosed rocks can be used to provide information on the sedimentary and tectonic history of a rock. There is often a relationship between the AMS of rock samples and the regional stress field of the area (Tarling and Hrouda, 1993). In undeformed sediments, the magnetic susceptibility is characterised by oblate ellipsoids, with a foliation coinciding with the bedding plane (i.e. the minimum axes of AMS, k_{min}, perpendicular to the bedding plane) and a random orientation of the lineation denoted by the maximum axes of AMS, k_{max}. If there is deformation acting on a rock, this initially results in a lineation, i.e. clustering of k_{max} in the direction of maximum extension or, equivalently, perpendicular to maximum compression. The k_{min} is still perpendicular to the

Fig. 2. Equal-area projections of characteristic remanent magnetisation (ChRM) results. Closed (open) circles represent downward (upward) projections. The circles give α_{95} for the different site means. (a) Western Crete, previously measured by Langereis (1984). (b) Central and eastern Crete, previously measured by Krijgsman et al. (1994, 1995).

bedding plane. An increase of the strain may cause the ellipsoid to have a more prolate structure, but this stage is never reached in the sections on Crete.

The anisotropy of the magnetic susceptibility was measured on a Kappabridge KLY-2 or KLY-3. Many of the AMS measurements from western Crete were previously carried out by Langereis (1984), and an additional 198 specimens were measured (total of 413 specimens) by us. All sections show oblate ellipsoids, the k_{min} axes being generally close to (but often significantly different from) the pole of the bedding plane, and the k_{max} axes are mostly WNW–ESE aligned (Figs. 3 and 5, Table 1). Error ellipses of the susceptibility axes are according to Jelinek (1978) and are given for k_{max} in Table 1. The majority of the lineations imply WNW–ESE extension, or corresponding NNE–SSW compression, except in the case of the Vasilopoulo, Makrilia and Apostoli sections which show considerable dispersion and near-random lineations (Fig. 3, Table 1).

3. Discussion and conclusions

Earlier, Valente et al. (1982) studied Late Miocene and Pliocene marine sediments on Crete. Their conclusion was that Crete did not undergo any significant rotation since Tortonian times. Kissel and Laj (1988) used this palaeomagnetic result to suggest that Crete as a whole has been decoupled from the western part of the Hellenic arc. This was based on the clockwise rotations found in the northwestern part of the Hellenic arc (Epirus, Ionian Islands and Peloponnesos) and a non-rotated southeastern section (Crete). Their ideas were supported by geological observations of Lybéris et al. (1982) and Angelier et al. (1982), and led to a palaeomagnetic reconstruction with an originally almost rectilinear E–W-trending Hellenic arc. Since these publications, a stable non-rotated position of Crete was used as a boundary condition in many kinematic studies of the Aegean region (Le Pichon and Angelier, 1981; Angelier et al., 1982; Taymaz et al., 1991; Westaway, 1991).

Our palaeomagnetic results from the late Tortonian to early Messinian sections, however, clearly show that predominantly counterclockwise rotations have occurred on Crete (Fig. 4) some time after the early Messinian. The largest counterclockwise rotations were found in central Crete. Considering the time-span of some of these sections it also follows that no differential rotations occurred during the interval 9.7–6.7 Ma. In western Crete, two groups of rotations are shown (~20° counterclockwise and ~0° rotation), which cannot be explained by different ages of the sediments. Because all sections were initially sampled for magnetostratigraphic purposes, care was taken to sample sections that are as long and continuous as possible, and to avoid sections which are disturbed by internal faults. Furthermore, the proven suitability of our sections for magnetostratigraphic correlation (see Langereis, 1984; Krijgsman et al., 1994, 1995) indicate that the magnetisation components are of primary origin. In addition, the sections show a positive reversal test (Langereis, 1984), which indicates that any secondary overprint has been successfully removed. There is one exception which concerns a subchron (zone D+; in Langereis, 1984) of very short duration (Krijgsman et al., 1994) during which the directions may have been subject to delayed acquisition (Van Hoof and Langereis, 1991). All other subchrons, however, share a common true mean direction, according to the test of McFadden and Lowes (1981).

Although we also observed three sections without any rotation, our predominantly counterclockwise results are not compatible with the conclusion derived by Valente et al. (1982) that Crete has not undergone any significant rotation with respect to Europe or Africa since middle Tortonian time. Valente et al. (1982) based their conclusion on the mean direction for all their Miocene sites being 356.5°. However, it appears that five of their fourteen sites also show counterclockwise results (up to 22.5°). This is not surprising considering the fact that at least several sites are sampled from the same outcrops as our sections. Additional palaeomagnetic data of central Crete (Kastellios Hill) by Sen et al. (1986) also revealed counterclockwise rotation (14°), although to a lesser extent than our average result (34°) for the same section. However, no confidence limits are given for their section. A large error in our mean direction (a counterclockwise rotation of 34 ± 15°) which is based on fewer samples, reflects the presence of some results with anomalously low inclinations (Fig. 2). Thus, the

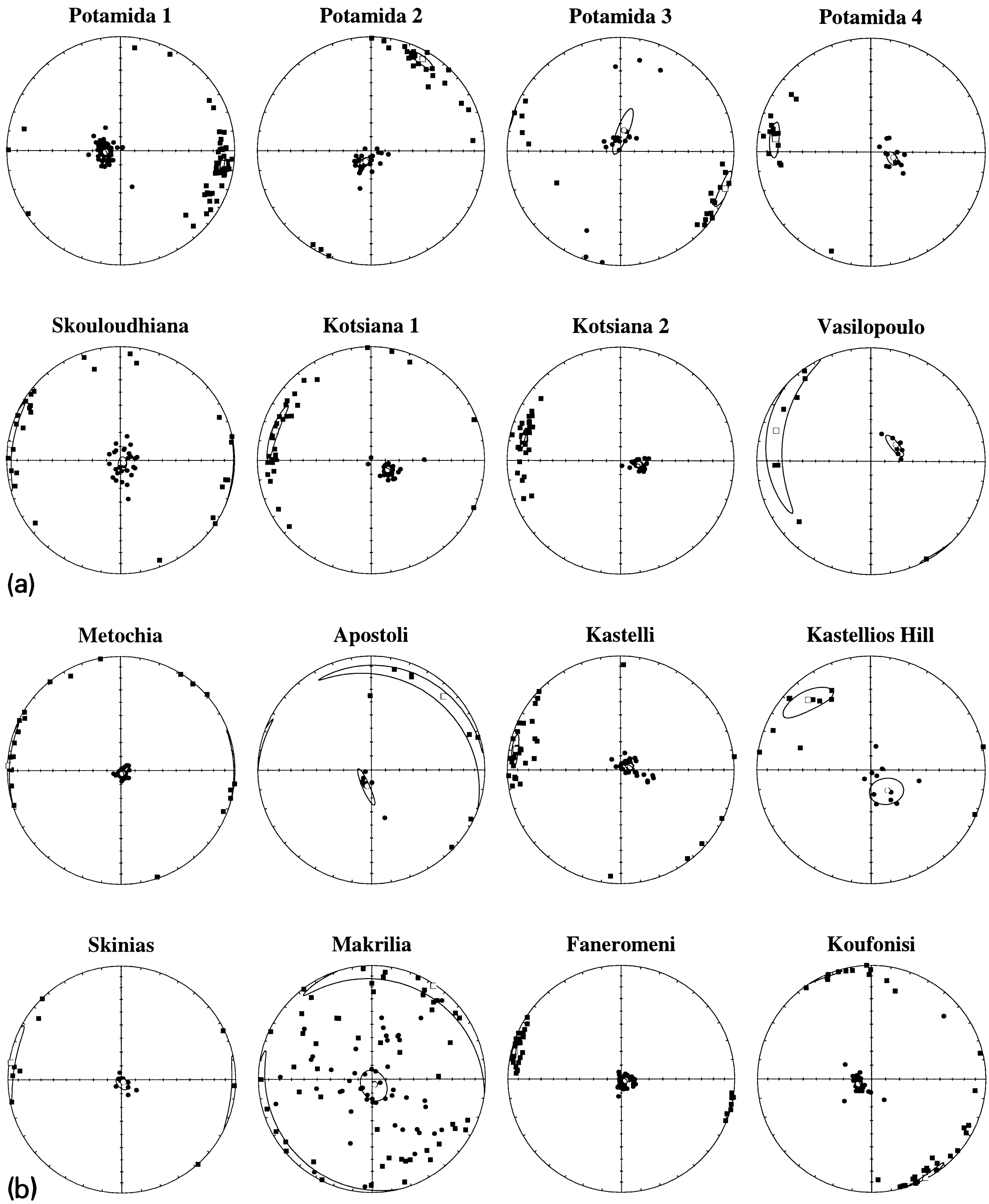


Fig. 3. Equal-area projections (bedding-tilt corrected) of k_{max} (squares) and k_{min} (circles) of the ellipsoid of the AMS for individual samples, with the calculation of mean ellipsoid for each site. (a) Western Crete. (b) Central and eastern Crete.

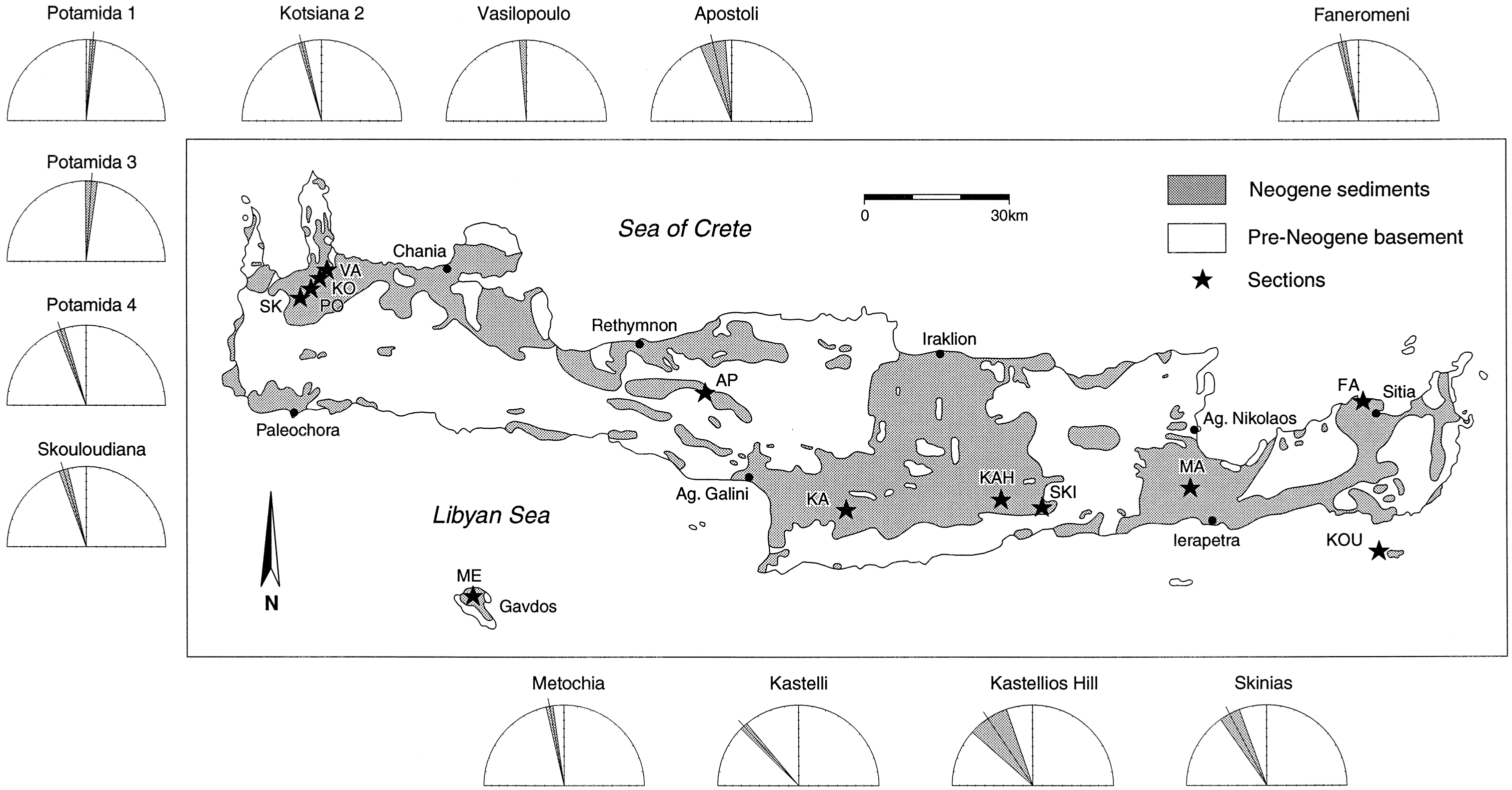


Fig. 4. Distribution of ChRM data on Crete; shaded segment represents α_{95} with solid line as mean declination per section. *PO* = Potamida; *SK* = Skouloudiana; *KO* = Kotsiana; *VA* = Vasilopoulo; *ME* = Metochia; *AP* = Apostoli; *KA* = Kastelli; *KAH* = Kastellios Hill; *SKI* = Skinias; *MA* = Makrilia; *FA* = Faneromeni; *KOU* = Koufonisi.

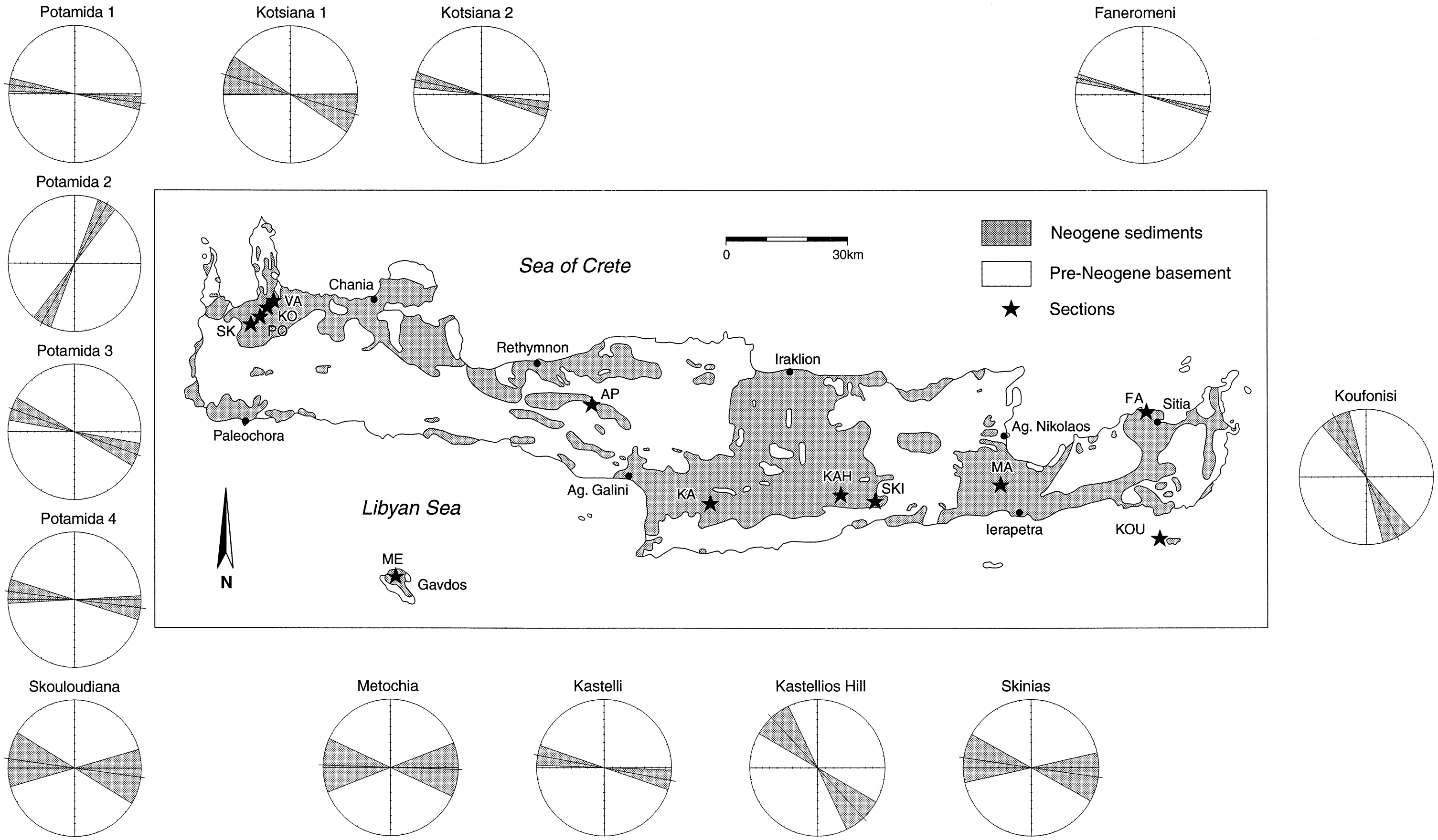
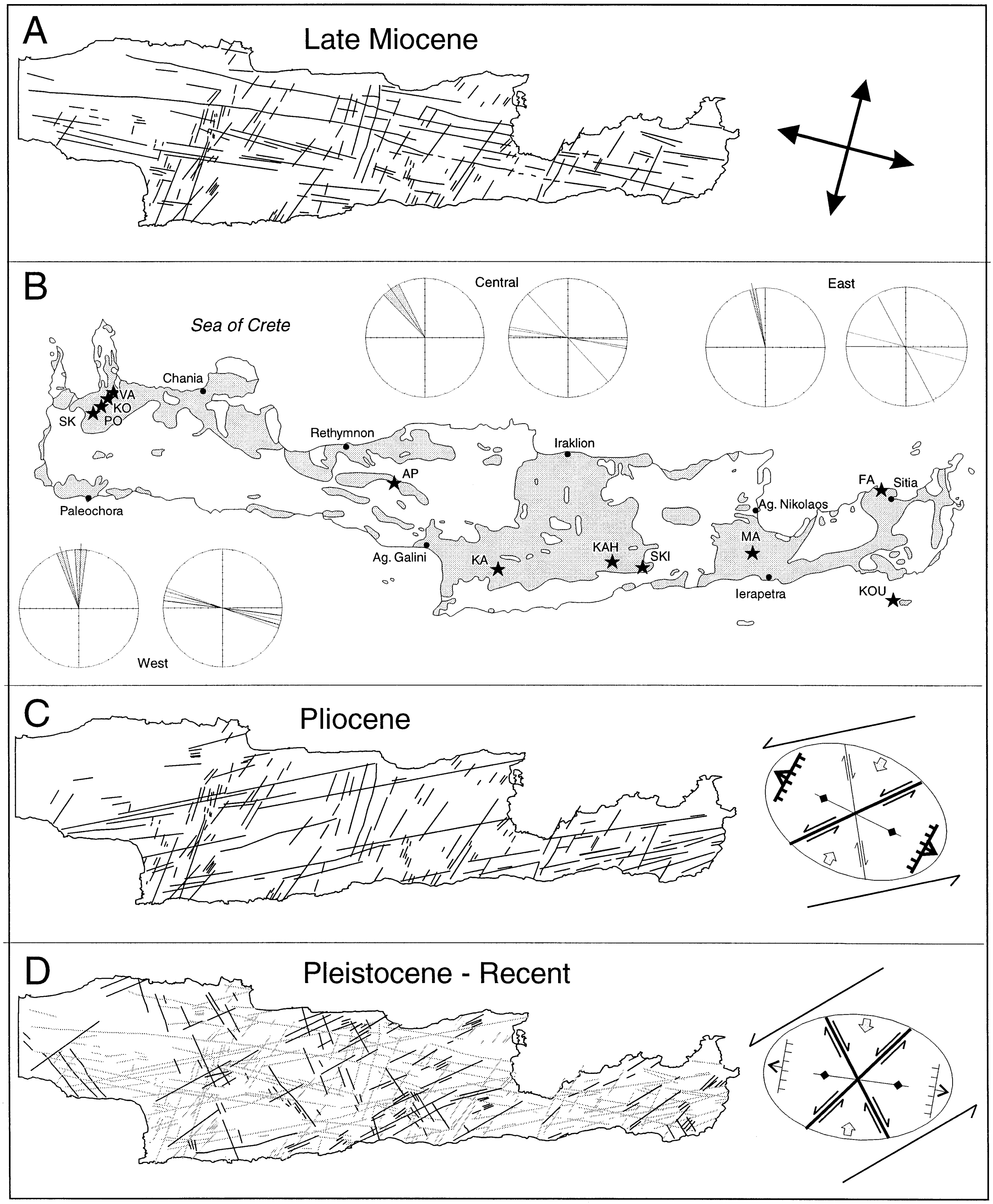


Fig. 5. Distribution of AMS data on Crete; shaded segment represents error on mean k_{max} axes (dAz) with solid line as mean lineation direction per section. *PO* = Potamida; *SK* = Skouloudiana; *KO* = Kotsiana; *ME* = Metochia; *KA* = Kastelli; *KAH* = Kastellios Hill; *SKI* = Skinias; *FA* = Faneromeni; *KOU* = Koufonisi. The near-random lineation results of the Vasilopoulo, Apostoli and Makrilia sections were omitted.


A
Late Miocene
B
Sea of Crete
Central
East
West
Chania
VA
KO
SK
PO
Rethymnon
Iraklion
AP
Paleochora
FA
Sitia
Ag. Nikolaos
MA
KAH
KA
SKI
Ag. Galini
Ierapetra
KOU
C
Pliocene
D
Pleistocene - Recent

results of the two studies do not necessarily disagree.

Our results, in addition to those of Valente et al. (1982) and Sen et al. (1986), show that in some cases no rotations but mainly counterclockwise rotations have taken place. This suggests that palaeomagnetic rotations are governed by (local) rotations of fault-bounded blocks, rather than Crete rotating as a single block. We note, however, that there is little evidence for clockwise rotations, and this helps constrain the overall tectonic regime.

Morris and Anderson (1996) have suggested a domain with clockwise rotations extending from northern Greece as far south as Mykonos. The southern boundary of this domain must lie between Mykonos which shows clockwise rotations and Naxos showing counterclockwise rotations (Morris and Anderson, 1996), and possibly south of Milos, where counterclockwise rotations were also found (Kondopoulo and Pavlides, 1990). Although the Cretan palaeomagnetic results do not indicate that Crete has rotated counterclockwise as a single block, at least the sense of the rotations is in good agreement with the more regional Aegean tectonic regime.

Numerical modelling was performed to calculate the intra-plate stress fields for various distributions of forces (Meijer and Wortel, 1996, 1997) and the results were compared with the observed deformation. Recently, this modelling was done for the entire Aegean region, but with emphasis on the deformation in the Cretan segment of the arc (Ten Veen and Meijer, 1998). Comparison of the stress pattern modelled with those inferred from tectonostratigraphic analyses derived from observed fault directions and their episodes of activity shows that from 11 to 5 Ma arc-normal pull was the dominant force generating radial tension. For the period from $\sim$5 Ma onwards, there is evidence for the activity of a sinistral strike-slip fault system. The model analysis shows this to be consistent with the presence of transform resistance in the eastern Aegean trenches (Fig. 6). This sinistral fault system can account for counterclockwise rotations of different fault-bounded blocks. The amount of counterclockwise rotation will depend on the size of the rotating block. We note that the largest counterclockwise rotations are found in central Crete, which corresponds to an area bounded by the largest and most active strike-slip (sinistral) faults (Ten Veen, 1998). The results of Ten Veen and Meijer (1998) are, thus, in good agreement with our new palaeomagnetic rotational results.

Our AMS analyses (Figs. 5 and 6) indicate a WNW–ESE extension or NNE–SSW compression direction which is roughly parallel to the extension–compression direction of the Pliocene to Recent, as shown by their stress ellipsoids (Fig. 6C,D). Correction of the observed lineations for the counterclockwise rotations results in a less consistent pattern of lineations. This indicates that the lineations are younger than the post-early Messinian rotations on Crete. A similar relation is observed by Scheepers and Langereis (1994), who suggested, based on palaeomagnetic data from southern Italy, that the end-phase of tectonic rotations corresponds (during compression) to blocking of the system, followed by the alignment of the lineation.

We conclude that during the change from radial extension in the late Miocene to a sinistral fault system in the Pliocene (Fig. 6), (local) block rotations occurred in response to the changing tectonic configuration. The NNE–SSW compressional or WNW–ESE extensional direction caused the lineations observed in our AMS results. These were induced after post-early Messinian counterclockwise rotations on Crete. Our scenario is in good agreement with the comparison of modelled stress patterns and observed fault patterns (Ten Veen and Meijer, 1998). The observed counterclockwise rotations may be explained

Fig. 6. Tectono-stratigraphic episodes of central and eastern Crete. Structures obtained from Landsat satellite imagery and field observations. Black lines indicate active structures and dashed lines represent reactivated faults. Fault activity is based on differential vertical motions of Cretan fault blocks as determined from geohistory analysis (burial history) applied to the stratigraphic cover of the blocks. The stress field is inferred from few observed kinematic indicators and the kinematics as inferred from stratigraphical and sedimentological data, allowing an impression of the state of stress during a certain episode. The orientation of the stress ellipses explains the deformation along the highlighted (bold) fault directions. (A) Late Miocene. (B) Overview of the tectonic rotations and AMS data of Crete, derived from palaeomagnetic research, per area. Shaded area represents α_{95} with solid line as mean tectonic rotation. In the AMS plot the solid line denotes the mean lineation direction. (C) Pliocene. (D) Pleistocene to Recent.

by arc-normal pull on an increasing curvature of the arc through time, aided by an additional east–west tension caused by transform resistance in the overriding plate, initiated at approximately 5 Ma.

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